LESSONS LEARNED FROM THE U.S. GEOLOGICAL SURVEY ABANDONED MINE LANDS INITIATIVE – 1997-2002[1]

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Abstract. Growth of the United States has been facilitated, in part, by hard-rock mining in the Rocky Mountains. Abandoned and inactive mines cause many significant environmental concerns in hundreds of watersheds. Those who have responsibility to address these environmental concerns must have a basic level of scientific information about mining and mine wastes in a watershed prior to initiating remediation activities. To demonstrate what information is needed and how to obtain that information, the U.S. Geological Survey implemented the Abandoned Mine Lands (AML) Initiative from 1997 to 2002 with demonstration studies in the Boulder River watershed in Montana and the Animas River watershed in Colorado. The AML Initiative included collection and analysis of geologic, hydrologic, geochemical, geophysical, and biological data. The synergy of this interdisciplinary analysis produced a perspective of the environmental concerns that could not have come from a single discipline. Two examples of these perspectives include (1) the combination of hydrologic tracer techniques, structural geology, and geophysics help to understand the spatial distribution of loading to the streams in a way that cannot be evaluated by monitoring at a catchment outlet, and (2) the combination of toxicology and hydrology combine to illustrate that seasonal variability of toxicity conditions occurs. Lessons have been learned by listening to and collaborating with land-management agencies to understand their needs and by applying interdisciplinary methods to answer their questions.

Additional Key Words: Hydrothermal alteration mineralogy, metal loading, ecotoxicology, risk assessment, science-based decisions

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Introduction

Growth of the United States has been facilitated, in part, by the hard-rock mining in the Rocky Mountains that has supplied the Nation with precious, industrial, and strategic metals. This mining, however, has left a legacy of acidic drainage and toxic metals in Rocky Mountain watersheds, with effects that present a potential threat to human and ecosystem health (Fields, 2003). In many areas, weathering of unmined mineral deposits and weathering of mine waste rock and mill tailings from historical mining combine to increase metal concentrations and lower pH to such an extent that fish and aquatic insects cannot survive in streams, and birds are negatively affected by the bioaccumulation of metals through the food chain (Larison et al., 2000). Although estimates of the number of inactive mine sites vary, observers agree that the scope of this problem is huge, particularly in the Western United States where public lands contain thousands of inactive mines.

Federal land-management agencies have inherited much of this legacy because numerous inactive mines affect aquatic or wildlife habitat on Federal lands. During the 1990s, land- and resource-management agencies recognized that they were faced with evaluating the risks associated with thousands of potentially harmful mine sites. In 1995, personnel from a U.S. Department of the Interior (DOI) and U.S. Department of Agriculture (USDA) interagency task force developed a coordinated strategy for the cleanup of environmental contamination from inactive mines associated with Federal lands. As part of this interagency effort, the U.S. Geological Survey (USGS) launched an Abandoned Mine Lands (AML) Initiative (http://amli.usgs.gov/) to develop a strategy for gathering and communicating the scientific information needed to formulate effective and cost-efficient remediation for these inactive mines.

The USGS AML Initiative was implemented in two study areas (Fig. 1), the Animas River watershed in Colorado and the Boulder River watershed in Montana. Comprehensive scientific investigations were conducted in both watersheds during 1997-2002 (Nimick et al., 2004; Church et al., 2006). The paramount goal of the Initiative was to develop tools for systematic evaluation of the ecological and environmental effects of historical mining within the framework of the watershed approach. Tools were needed for characterizing effects at the watershed and site scales; understanding of the sources, extent, and effects of metals and acidity; and communicating the results to stakeholders, land managers, and the general public. Another objective was to transfer the tools developed within the AML Initiative into practical methods at the field scale and to demonstrate their applicability to solve this national environmental problem in a timely manner. A final objective was establish a scientific basis for consensus by developing working relations with the private sector, local citizens, and State and Federal land-management and regulatory agencies, and thus set an example for future investigations of watersheds affected by inactive historical mines (Buxton et al., 1997).

There are several ways to look at the lessons we learned through the AML Initiative. First, we could look at the new science that we learned. Details of this science are summarized in technical reports for the two study watersheds (Nimick et al., 2004; Church et al., 2006). In this synthesis, however, we take a different perspective. Instead of looking at discipline-specific results, we look at what we learned from bringing together different scientific disciplines and their different frames of reference, and how we provided information and real-time advice to land-management agencies. In particular, we look at how interaction among scientific disciplines created new questions or made us rethink old questions, and we present two examples where a multidisciplinary approach resulted in novel results. In addition, we look at what we have learned about giving advice to land-management agencies and review the needs and limitations of communicating results to these decision makers.

Figure 1. Location of demonstration watersheds for the Abandoned Mine Lands Initiative.

New Questions from a Synthesis of Different Views

During the AML Initiative, USGS scientists from different disciplines have learned that we approach problems from many different perspectives. How we ask our questions, and the context we give them, makes a difference in the perceived value of our results to land-use managers. John Harte, of the University of California-Berkeley, recently discussed the process of bringing together views from different scientific disciplines and summarized some of the differences in thought between Newton and Darwin perspectives (Harte, 2002). This list shows why putting physicists and ecologists together to study the same problem requires each to pose the questions they ask in different terms or in a different context:

Physics	Ecology
The more you look, the simpler it gets	The more you look, the more complex it gets
Primacy of initial conditions	Primacy of contingency and complex historical factors
Universal patterns; search for laws	Weak trends; reluctance to seek laws
Predictive	Mostly descriptive, explanatory
Central role for ideal systems	Disdain for over-simplified views of nature

A list of the disciplines that were involved in the AML Initiative and the "tools" or methods used in each discipline to answer general questions are contained in Table 1. The uses of these tools in different disciplines of the AML Initiative have been linked to chapters in the two summary volumes in the right-hand column of Table 1. The level of scientific study we conducted in these watersheds likely will not be feasible in future studies of watersheds affected by historical mining. But our experience helps provide guidelines for choosing those tools that may be critical to characterization and analysis of any individual watershed. Synthesis of results from these disciplines offered opportunities for progress that were not otherwise available, bringing together disparate views of the watershed to yield a better understanding.

Table 1. "Tools" available in multidisciplinary study of abandoned mine lands.

[Use in summary reports refers to chapters in Animas (Church et al., 2006) and Boulder (Nimick et al., 2004) summary reports; AMD, acid mine drainage; ARD, acid rock drainage]

Discipline	"Tool," method, or instrumentation	Question answered	Use in summary reports
Mining geology / history	Evaluate historical records of mining	Where are the ore deposits and historical mines? How much have they produced and to what extent have the deposits been mined?	Animas C, E3, E5, E6; Boulder D3, D4
Geologic framework	Evaluate previous geologic reports in the context of AML study.	What are the tectonic and structural controls on ore deposits?	Animas B, E1, E4; Boulder B, D1, D2

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Discipline	“Tool,” method, or instrumentation	Question answered	Use in summary reports
Petrology and mapping	Evaluate geologic formations, lithology, chemistry, and hydrothermal alteration history	What is bedrock (background) composition? What are the predominant ore types? What is the extent of regional hydrothermal alteration?	Animas B, E1, E3, E13, E15, E16; Boulder D1, E3
Mineralogy	Survey bed sediment chemistry	What is the extent of metal contamination downstream from areas of mining?	Animas D, E12, G; Boulder C, D8, G
Mineralogy	Airborne visual/infrared imaging spectrometry (AVIRIS)	Are there important regional and local patterns of hydrothermal alteration?	Animas E2
Mineralogy	Stream survey	Sedimentology and mineralogy of bed sediment, locations of possible ground-water inflows to stream	Animas D, E12, E14, E15, E16, E18; Boulder C, D8
Mineralogy	Airborne geophysical methods	Where are geologic units with more or less acid neutralizing potential	Boulder D2
Geophysics	Airborne geophysical methods	What are the fracture networks and do they transport mine drainage?	Animas E4, E13; Boulder D2, D9, E3
Geomorphology	Survey of mine waste erosion and deposition	What does the geomorphology of stream valleys tell us about mining history?	Animas E16, E22

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Discipline	"Tool," method, or instrumentation	Question answered	Use in summary reports
		Are there geomorphic controls that affect the transport of metals?	
Hydrology / aquatic geochemistry	Mass-loading studies	Where does water enter the streams, and how much comes in? What are the metal loads associated with these inflows?	Animas E9, E23, E24; Boulder D6, E1
Hydrology / aquatic geochemistry	Water-quality sampling and geochemical analysis	What is the background geochemistry of water affected and unaffected by AMD or ARD? What processes affect the solutes?	Animas D, E5, E7, E8, E9, E10, E11, E14, E15, E16, E17, E23, E24, E25; Boulder C, D5, D6, D7
Hydrology / aquatic geochemistry	Stream gaging; seasonal water-quality sampling	What are the daily, seasonal, and annual variations of discharge and solute loading? Has remediation improved water quality?	Animas B, E10, E11, E19; Boulder B, D5, D7, E2
Hydrology / aquatic geochemistry	Spring and adit water-quality sampling	What is the background water-quality?	Animas E7
Hydrology / aquatic geochemistry / ecology and ecotoxicology	Monitoring	Have remediation goals been accomplished?	Animas E23, F

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Discipline	“Tool,” method, or instrumentation	Question answered	Use in summary reports
Ecology and Ecotoxicology	Fish, benthic invertebrate community survey	Are stream biotic communities altered in AMD-affected areas?	Animas D, E18, E20 Boulder C, D10
Ecology and Ecotoxicology	Habitat characterization	Does physical habitat limit recovery of aquatic biota?	Animas E21
Ecology and Ecotoxicology	Fish health assessment	Is fitness of resident biota compromised by mining?	Animas D; Boulder C, D10
Ecology and Ecotoxicology	On-site toxicity tests	Can aquatic biota tolerate exposure to ambient water and/or sediments? Does toxicity vary seasonally?	Animas E19 Boulder D10
Ecology and Ecotoxicology	Laboratory toxicity tests	What concentrations of metals are associated with toxic effect for species of interest?	Animas D, E19; Boulder C, D10
Ecology and Ecotoxicology	Ecological risk assessment	What are the current risks of toxicity for aquatic species of interest across the study area? What level of remediation will be required to ameliorate toxic effects?	Animas D Boulder C
Data presentation	Spatial data relations, geographic information systems, mapping	What are spatial relations among the many sites studied? How have sources of	Animas A, G; Boulder A, G

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Discipline	“Tool,” method, or instrumentation	Question answered	Use in summary reports
		metals affected water and sediment quality in downstream reaches?	
Data base management	Preparation of relational data base	What data are available?	Animas G; Boulder G

Examples of Conducting Integrated Science

There are many instances where bringing together different disciplines has affected the results of the AML Initiative in a positive way. To illustrate how this has happened, two examples are provided.

Structural geology, hydrothermal-alteration, mapping, and mass loading

Individual studies of geologic structure, hydrothermal-alteration mapping, and mass loading to streams can make important contributions to the characterization of a watershed. When considered together, however, they lead one to consider the influence of structure and hydrothermal alteration on metal loading. In the Animas River watershed, the structural geology indicated that an extensive bedrock fracture and fault network developed in response to the caldera-related volcanic and tectonic history of the region. The network consists of northwest-to-southeast trending faults and veins that are radial to a caldera-ring fault zone. This network of structures can influence the hydrologic system today because many individual structures were only partially affected by mineralization and extend laterally and vertically from tens of meters to a few kilometers. In particular, fractures that are densely spaced, unfilled by subsequent mineralization, and interconnected may focus near-surface ground-water flow at the local or sub-basin scale.

The extensive regional hydrothermal alteration facilitated by these structures creates many potential sources of metals and acidity. Multiple hydrothermal alteration and mineralization events that span from about 27 to 5 million years (Ma) are the culmination of a complex cycle of volcanic and tectonic events that have affected the region (Lipman et al., 1976; Bove et al., 2001). The first episode of hydrothermal alteration formed during the cooling of the San Juan caldera volcanic fill, when lava flows cooled and degassed, releasing large quantities of CO_2, among other volatile constituents such as SO_2 and H_2O. This event altered the primary mineral assemblage of the lava flows and formed a propylitic alteration assemblage that includes calcite, epidote, and chlorite (Burbank 1960), part of the pre-ore propylitic hydrothermal assemblage, which has a high acid-neutralizing potential (Desborough and Yager 2000). Mineralization events that post-dated the prophylitic hydrothermal assemblage contained S-rich hydrothermal fluids and metals that produced various vein and hydrothermal-alteration mineral assemblages, all of which include abundant pyrite (Burbank and Luedke 1968; Casadevall and Ohmoto, 1977).

Host rock hydrothermal alteration in many places throughout the Animas River watershed study area effectively removed the acid-neutralizing mineral assemblage of calcite-epidote-chlorite from these subsequently altered areas, particularly in the Mineral and Cement Creek basins.

Most of the mineralization events that overprint rocks affected by regional propylitization in the study area may be subdivided into three broad categories on the basis of age and style of mineralization (Bove et al., 2006). The earliest event was a low-grade molybdenum-copper-porphyry mineralization (Ringrose 1982; Bove et al., 2001). Progressively outward from the locus of mineralization, concentric zones of quartz-sericite-pyrite, weak-sericite-pyrite and prophylitically altered igneous and volcaniclastic rocks, respectively, form the periphery of this hydrothermally altered and mineralized porphyry system. A younger, acid-sulfate system formed at 23 Ma and developed in response to the emplacement of coarsely porphyritic dacite intrusions. The two largest areas of this hydrothermal alteration occurred in the vicinity of the Red Mountains, in the area near Ohio Peak and along Anvil Mountain, which forms the drainage divide between Mineral and Cement Creeks (Fig. 2). Acid-sulfate mineralization in the Red Mountain area is often characterized by breccia-pipe and fault-hosted vein ore with abundant copper-arsenic-antimony-rich minerals such as enargite-tetrahedrite-tennanite, in addition to chalcocite, bornite, and covellite (Bove et al., 2006). The third and most economically important episode of mineralization formed post 18-Ma and is closely associated with the emplacement of high-silica alkali rhyolite intrusions (Lipman et al., 1973). Mineral deposits formed during this episode consist of polymetallic, Cu-Pb-Zn base- and precious-metal veins that were deposited along caldera-related northwest-southeast trending fractures tangential to the Silverton and San Juan calderas, and along primarily northeast-southwest trending graben faults and some northwesterly-trending faults that originally developed during resurgence of the San Juan caldera (Varnes 1963; Casadevall and Ohmoto, 1977). Late-stage gangue minerals include anhydrite, fluorite, calcite, and gypsum (Casadevall and Ohmoto, 1977). Unlike the pervasive areas of hydrothermal alteration that are associated with both the porphyry Mo-Cu mineralization and acid-sulfate mineralization systems that often affects entire mountain blocks, post-18 Ma hydrothermal alteration tends to be focused adjacent to veins and vein structures.

During the AML Initiative, a series of 13 synoptic tracer-injection studies established a hydrologic framework to quantify metal loading within the Animas River watershed (Kimball et al., 2006), a level of hydrologic and geochemical detail never before collected to study mine drainage. Results have allowed stakeholders to prioritize mine-site remediation at the watershed scale (Kimball et al., 2002; U.S. Geological Survey 2000). However, the patterns of metal loading defined by the synoptic studies take on new meaning when interpreted in the context of the structural and hydrothermal alteration patterns. These geologic patterns help explain why and where mined as well as unmined areas contribute substantial loads of metals and acid to the streams.

Within the three principal basins, 24 locations, including surface inflows and areas of subsurface inflow draining both mined and unmined areas, accounted for 73 - 87 % of the total mass loading of Al, Fe, Cu, Zn, and Mn. These locations mostly correspond to locations of the pyrite-rich alteration types (Fig. 2). For example, dispersed inflows near Red Mountain Pass (location B, in Mineral Creek basin), as well as water draining the Koehler tunnel (location A, in Mineral Creek basin) contributed substantial Cu and Zn loads. This is an area of acid-sulfate alteration, and the breccia pipes contributed greatly to the loads. The unmined sources (location B) account for 37 kg/day of Zn load, which is one of the largest single sources of Zn to

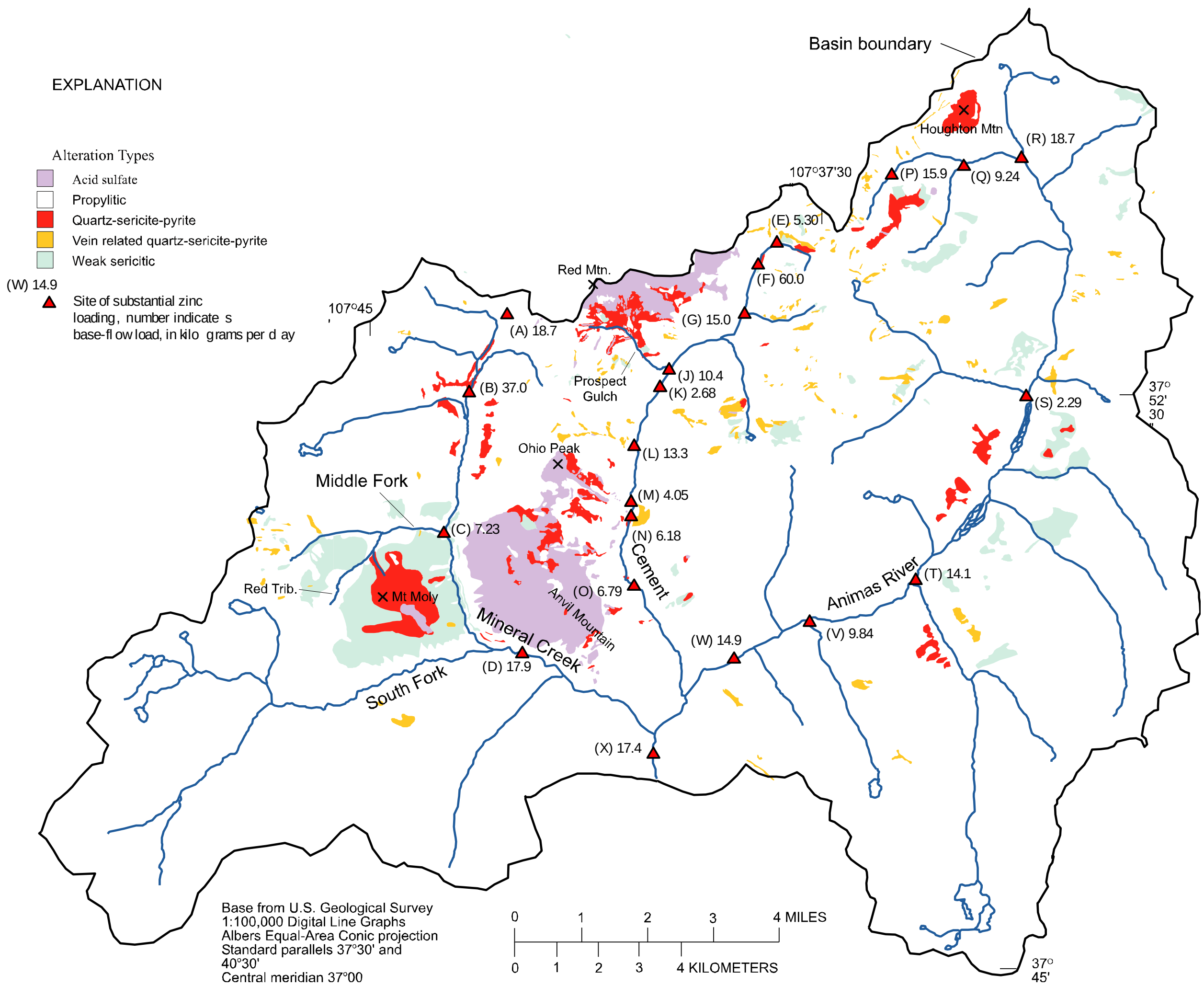

Figure 2. Locations and base-flow quantities of principal locations for zinc loading.

the Animas River watershed (Kimball et al., 2006). Weathering of extensive acid-sulfate and quartz-sericite-pyrite alteration zones near Red Mountain, along the Middle Fork of Mineral Creek, and near Anvil Mountain provides much of the Zn loading to the Mineral and Cement Creek basins and substantially contributes to loading of Al and Fe. The location of greatest Al loading was the Middle Fork Mineral Creek (location C, Fig. 2), which drains extensive areas of quartz-sericite-pyrite alteration. Substantial Al and Fe loads also entered Cement and Mineral Creeks where they drain the acid-sulfate alteration of Ohio Peak (locations D, M, and N, Fig. 2, in Cement Creek basin) and Anvil Mountain (locations D and O, Fig. 2, Mineral and Cement Creek basins). Also in the Cement Creek basin, both Prospect (location J) and Minnesota Gulches (location L) drain acid-sulfate and quartz-sericite-pyrite alteration and contributed substantial Al and Fe loads. Mineral Creek basin dominated the contribution of total Cu load, whereas Cement Creek had the greatest contribution of total Zn load. The Mogul mine (location F) in Cement Creek, which may tap the mine pool behind the bulkhead in the American tunnel (Kimball et al., 2006), and the North Fork Cement Creek (location G) contributed large loads of

Cu and Zn. In contrast to the Cement and Mineral Creek basins, the Animas River basin drains mostly regional propylitic alteration (Fig. 2). As a result, the Animas River does not have comparable loads of Cu. Areas of vein-related quartz-sericite-pyrite alteration in the headwaters of California Gulch (locations P and Q), however, contributed substantial Mn and some Zn loading. Fluvial deposits of mill tailings and tailing piles that contain Mn gangue minerals contribute substantial loads of Mn and Zn to the Animas River downstream from Arrastra Creek (locations V and W).

With the high cost of remediation, a predictive tool based on sound science that could be used to anticipate results of various remediation options is a desirable objective of any watershed characterization effort, particularly if it could be used in conjunction with the best state-of-the-art engineering solutions to make informed and cost-effective remediation decisions. Reactive transport models were developed for this purpose during the AML Initiative (Walton-Day et al., 2006). Scenarios for various remediation solutions have been run for selected stream reaches in the Animas River watershed. These models integrate the synoptic discharge and water chemistry from tracer studies, and remediation options come from knowledge of the geologic structure and hydrothermal alteration.

Hydrology and ecotoxicology

Besser and Leib (2006) concluded that remediation of acid-generating mine wastes with the goal of stream ecosystem recovery requires an understanding of the mechanism by which metals adversely affect stream biota. The AML Initiative provided an opportunity to combine characterization of seasonal variation in stream discharge and dissolved metal concentrations (Leib et al., 2003) with characterizations of toxic effects of metals to sensitive aquatic species under site-specific exposure conditions (Besser et al., 2001). Toxicity tests with stream water and laboratory-prepared Cu and Zn solutions determined that sensitivity to these metals differed substantially among the three tested species: fathead minnows (*Pimephales promelas*), amphipods (*Hyalella azteca*), and brook trout (*Salvelinus fontinalis*) (Besser et al., 2001). On the basis of measured range of sensitivity of each species to Cu and Zn toxicity and on the seasonal variations of dissolved Cu and Zn concentrations, Besser and Leib (1999) modeled seasonal variation in toxicity of these metals at three gaging stations that had long-term records of discharge and concentration. These models predicted severe toxic effects of Zn for amphipods at all three stations year-round, and seasonally toxic effects on brook trout at one station. Models for both metals predicted greater toxicity during late winter, consistent with results of toxicity tests with stream water (Besser et al., 2001; Fey et al., 2002). The toxicity thresholds validated by this synthesis of hydrologic, chemical, and ecotoxicological data were used as the basis of a watershed-scale ecological risk assessment (Besser et al., 2006) that characterized risks of metal toxicity in streams of the upper Animas River watershed. Color-coded maps of toxicity risks for stream segments (Fig. 3) are valuable tools for communication of current conditions and for prioritization of remediation efforts.

Communicating Results to Land-Management Agencies

Communicating scientific results in a way that makes them useful to non-scientists has always been a challenge. A main purpose of the AML Initiative was to identify what scientific information would best fit the needs of land managers to be able to make sound decisions as described in Table 1. The discussion here presents a description of recommended actions for making science-based decisions that take advantage of the tools to accomplish those actions.

In an AML watershed study, there are different phases of study that mostly occur in sequence (Table 2). These include 1) screening, 2) characterization, 3) investigation, and 4) monitoring. For each of these phases, there are four steps: identifying contaminant sources, defining contaminant processes and transport, establishing the extent of injury to ecosystems, and finally, making recommendations to decision makers.

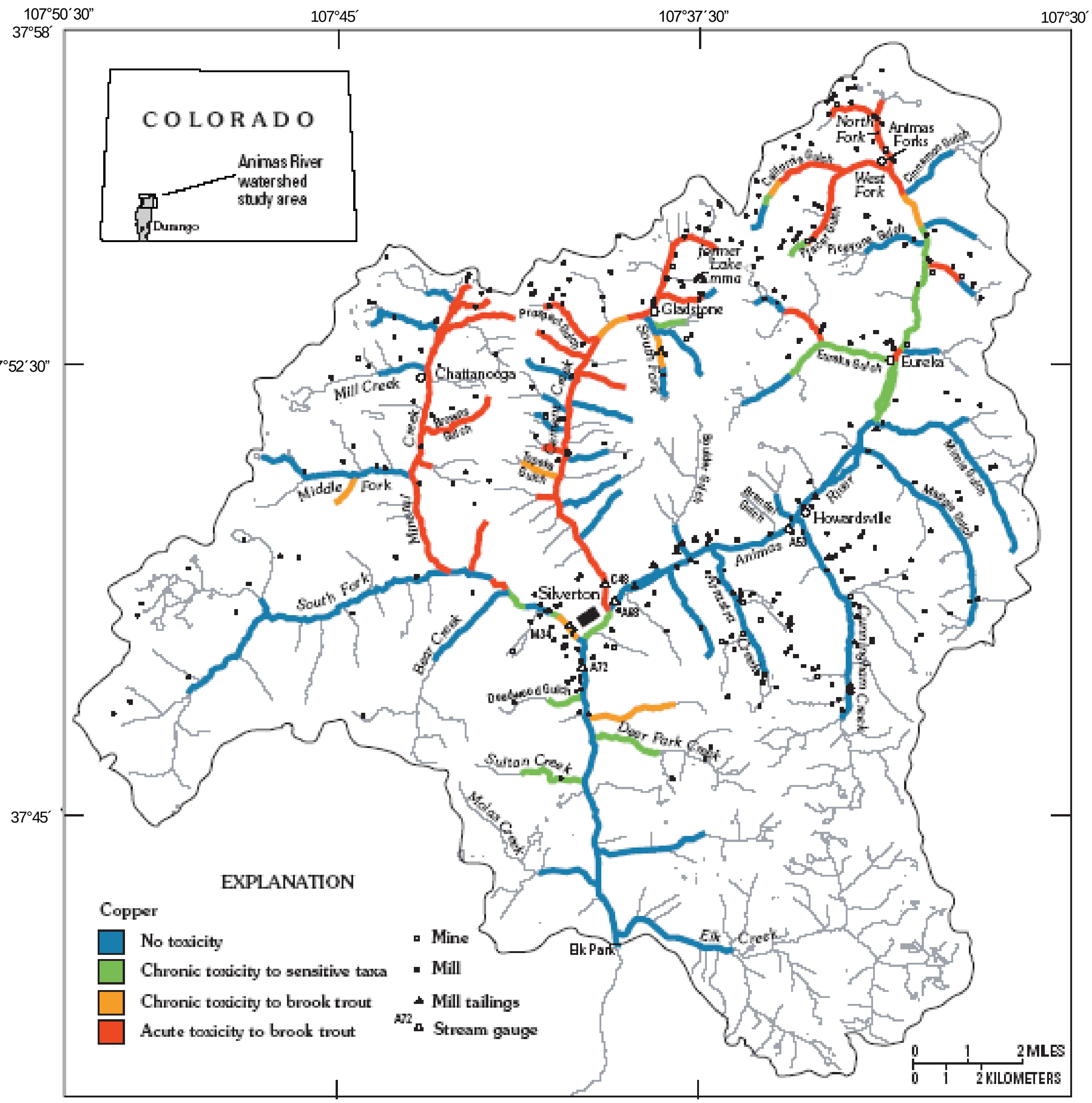

Figure 3. Ecological risk assessment due to Cu toxicity for the Animas River watershed

Within a targeted watershed, screening activities would focus on determining the extent of contamination, the source of contaminants, and the processes affecting contaminant transport. Biological investigations can greatly aid in this screening to understand the scope of problems that may exist. With the screening, it becomes possible to make recommendations for an initial list of priority sites in a watershed. In the watershed characterization phase, each of these steps will become more detailed as indicated in Table 2. The greater detail can result in a ranking of sites for remediation. If the amount of acid mine drainage (AMD) compared to non-mining-related acid rock drainage (ARD) is large, then sites might be identified and chosen for remediation as a result of this phase. However, if there is a large amount of ARD in the watershed, then additional steps are recommended to allow an informed decision on the value or benefit of remediating sources of AMD. If the extent of ARD is very large, remediation in the watershed may not be able to accomplish the desired goals. The final phase, after remediation, is monitoring to understand what has been done and to know if objectives of remediation have been accomplished (Finger et al., 2004; Finger et al., 2006). Information from monitoring should be used to evaluate the effectiveness of the actions leading to remediation decisions.

Each of these recommended actions (Table 2) uses techniques, methods, and instruments listed in Table 1. Uses of these tools in different disciplines of the AML Initiative have been linked to chapters in two summary volumes (Church et al., 2006; Nimick et al., 2004). Technological advances continually produce new methods and instruments that can improve our ability to make these investigations. To keep up with innovations, the process, suggested in Table 2, should be evaluated often.

Table 2**.** Suggested actions for the Federal land-management agencies for conducting a study of abandoned mine lands

[FMLA, Federal land-management agencies; AMD, acid mine drainage.]

Identify Sources of Contaminants	**Define Contaminant Processes and Transport**	**Establish Injury to Receptors and Identify Contaminant Pathways**	**Provide Recommendations to FLMA**
	Watershed Screening Phase		
1. Arrange access to private sites and determine likelihood that a responsible party is present in watershed 2. Obtain digital topography, roads, and stream coverages 3. Identify mine waste deposits that are >100 tons within ¼ mile of streams using available inventories and sample all on	1. Conduct synoptic studies to determine major sites of contaminants loading along stream reaches 2. Characterize water quality and discharge from major adits and springs 3. Determine sediment load characteristics and document dispersion of contaminated sediment	1. Collect biofilm and invertebrate populations at same sites as sediment samples to determine impact of AMD on food chain 2. Collect instream and pore waters for laboratory toxicity studies 3. Evaluate wetlands and riparian habitats as possible sinks for metals	1. Identify those sites in the watershed that should have first priority for removal based on watershed-scale impact 2. Identify possible repository sites based upon lithology, structure, topography, and access in consultation with decision makers 3. Identify stream reaches that have highest promise for

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[FMLA, Federal land-management agencies; AMD, acid mine drainage.]

Identify Sources of Contaminants	Define Contaminant Processes and Transport	Establish Injury to Receptors and Identify Contaminant Pathways	Provide Recommendations to FLMA
accessible lands 4. Locate major mill sites, periods of production, for environmental impact 5. Evaluate stream reaches for possible aggregation of metal-rich sediment 6. Identify and sample likely sites of ground-water inflows along stream reaches 7. Determine mineral deposit type, geologic setting, lithology, extent of hydrothermal alteration, and buffering characteristics of rocks 8. Identify and characterize geology of possible repository sites	4. Evaluate plausibility of possible mercury contamination based on mineral deposit type and production history 5. Develop solute transport model from synoptic data	4. Evaluate suitability of fish habitat and estimate fish populations stream reaches 5. Evaluate stream reaches downstream from mill sites for phytotoxic impacts on riparian habitat 6. Rank stream reaches that can readily be restored to provide suitable physical fish habitat	rapid recovery of good aquatic and riparian habitat 4. Recommend monitoring program for evaluating effectiveness of restoration work 5. Determine if stream gage needed if not present in watershed 6. Recommend scale of effort that should be undertaken to characterize watershed sufficiently before remediation work can be completed

Table 2. Suggested actions for the Federal land-management agencies for conducting a study of abandoned mine lands

[FMLA, Federal land-management agencies; AMD, acid mine drainage.]

Identify Sources of Contaminants	Define Contaminant Processes and Transport	Establish Injury to Receptors and Identify Contaminant Pathways	Provide Recommendations to FLMA
Watershed Characterization Phase			
1. Evaluate anthropogenic and background sources of contaminants using results of tracer work 2. Sample contaminant sources identified by tracer 3. Determine possible ground-water components 4. Identify anthropogenic and fluvial sites where mercury might be expected to accumulate 5. Determine metal concentrations in premining stream sediment deposits	1. Evaluate seasonal and diurnal variation in stream water chemistry and controlling processes 2. Complete inventory of inflows from sites along stream reach 3. Identify structural and ground-water pathways for major inflows 4. Sample sites where mercury might be expected to accumulate	1. Determine fish populations and distributions at selected sites suitable for long term monitoring of watershed 2. Determine 96-hour LC50 using hatchery fish at selected monitoring sites in watershed 3. Determine invertebrate community structure 4. Core or trench possible phytotoxic stream reaches to determine impact of mining and milling practices on aquatic and riparian habitats 5. Determine sublethal toxicity effects caused by different metals and ratios in water, sediment, and food chain (i.e. mineral deposit type context)	1. Using data sets collected on characteristics of sources, use solute-transport model to calculate likely impact on watershed chemistry by removing discrete sources of contaminants. This will allow FLMA to do cost/benefit calculations to rank remediation options within the watershed 2. Recommend maximum cleanup goals that can be reached on basis of premining contaminant levels 3. Recommend fluvial reconstruction goals needed to restore viable aquatic and riparian habitat 4. Recommend additional removal actions that would improve watershed water quality

Table 2. Suggested actions for the Federal land-management agencies for conducting a study of abandoned mine lands

[FMLA, Federal land-management agencies; AMD, acid mine drainage.]

Identify Sources of Contaminants	Define Contaminant Processes and Transport	Establish Injury to Receptors and Identify Contaminant Pathways	Provide Recommendations to FLMA
Additional Watershed Investigation Phase (if the component of natural acidic drainage is large)			
1. Digitize geologic base map from published sources 2. Develop environmental lithologic map from geochemical and hydrothermal alteration data 3. Determine structural controls on fracture-flow for groundwater 4. Determine impact of mining on groundwater chemistry 5. Use remote sensing and/or geophysical data to evaluate groundwater flow paths	1. Determine ground-water pathways for contaminants 2. Quantify fluxes and contributions from undisturbed altered areas within watershed 3. Determine isotopic signatures of waters and sediments to quantify source loads and trace impact on watershed 4. Develop watershed scale rainfall/runoff and solute transport model for watershed	1. Estimate water quality conditions that would have existed prior to mining 2. Predict possible community structure that would have existed prior to mining	1. Using data collected on characteristics of sources, use rainfall/runoff and solute-transport models, environmental geology, biological data, and ground-water inflows to calculate likely impact on watershed chemistry by removing discrete sources of contaminants. This will allow decision makers to do cost/benefit calculations to rank remediation options within the watershed.

Table 2. Suggested actions for the Federal land-management agencies for conducting a study of abandoned mine lands

[FMLA, Federal land-management agencies; AMD, acid mine drainage.]

Identify Sources of Contaminants	Define Contaminant Processes and Transport	Establish Injury to Receptors and Identify Contaminant Pathways	Provide Recommendations to FLMA
	Watershed Monitoring Phase		
1. Develop measures of success to be achieved by restoration	1. Monitor water and sediment quality changes over 3-5 year period following remediation. Once data appear to indicate that water quality has stabilized, conduct post-remediation synoptic study to evaluate success of remediation efforts	1. Evaluate improvement in water quality by monitoring improvement in invertebrate communities, habitat, metal concentrations in sediment biofilm and aquatic organisms, and 96-hour LC50 tests on hatchery fish	1. Recommend changes in land and recreational management practices for areas where removal of contaminated material not feasible.
	2. Calculate effects of improvements on overall water and sediment quality that has resulted from specific source removals		

Perhaps the most important things the USGS has learned from the AML effort is to listen to land-management personnel, understand their data and information needs, and to apply the tools that are available to answer their questions. Results from USGS scientific investigations are available in two stages. First, results are available before peer review and publication and need to be communicated to FLMAs to help in making decisions. Second, results are formally published. The time needed for publication, as a result of peer review and processing, can frustrate land managers who need to make science-based remediation decisions in a timely manner. Three possible ways to deal with the peer-review process and still meet the needs of managers are suggested. First, AML-type studies should be initiated early in the process of decision making so that results will be available to support the decisions. Second, seminars and workshops should be scheduled so that the scientists and land managers can communicate results as the scientific peer-review process proceeds (U.S. Geological Survey 2000; U.S. Geological Survey 1998). Third, FLMAs can use consultants or in-house expertise to develop information in order to meet tight time frames.

In summary, the AML Initiative has provided an opportunity for scientists from different disciplines to work together. We have learned to ask questions differently, often using a different point of view, and have seen how answers from different disciplines might help answer our own questions. The great benefit of interdisciplinary study for environmental problems is that complex problems, which may be too complex for individual researchers, can be understood and solved.

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